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Gas flow structure during submillimeter the arc discharge motion in transverse magnetic field

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The paper presents the results of experimental studies of the structure of the near-wall flow arising when the plasma of a submillimeter arc discharge moves in magnetic field in stationary gas near the surface. Due to high accuracy of the process synchronization, we succeeded in obtaining the flow-velocity vector fields by using the adaptive PIV method with averaging them over a series of images. The main stages of the flow evolution at different magnetic field magnitudes are demonstrated for the first time; those stages are characterized by a stable dynamics of the homogeneous jet transformation into a complex vortex structure.

Keywords: arc discharge in magnetic field, magnetohydrodynamic flow, visualization of unsteady pulse processes.

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When the gas flows around structural components of aircrafts, channel walls of various devices, and propulsion systems, various gas-dynamic processes are be observed which arise during interaction of the oncoming gas flow with surface under the impact of viscous friction forces. Since the energy storage and generation techniques continue being improved, methods for controlling near-wall flows based on magnetoplasma technologies find application at present [1–3]. The main advantages of those methods are the rate of affecting the flow, local character of interaction, and variability of the spatial and energy parameters to be implemented. A special place is occupied by studies associated with using various-type electric discharges to control the flow structure near streamlined bodies in different-geometry channels [4–7]. Recently there were published studies aimed at creating actuators based on arc discharges moving in external magnetic field [8,9]. The arc discharge is known for simplicity of technical implementation and stable form of combustion in a wide range of environmental parameters. The here-studied method of creating bulk forces in a thin near-wall gas layer by using submillimeter arc discharges in constant magnetic field is aimed at changing the flow structure directly in the boundary layer bulk, which can increase the efficiency of the method even under the supersonic flow conditions.

Experimental studies of the magnetic field effect on the structure of the flow arising during the motion of the submillimeter arc discharge plasma in stationary gas were carried out using a chamber open to the atmosphere. Inside the chamber there was mounted a plate with electrodes and a magnetic field source (Fig. 1, *a*). A single electric discharge pulse about $50\,\mu$s long (Fig. 1, *b*) was initiated between two circular point electrodes mounted flush with the dielectric surface 2.2 mm apart each other. High-frequency electric current pulses were produced by a generator developed at ISP SB RAS. The peculiar feature of the generatorś operation was exploiting an igniting high-voltage pulse less than $1\,\mu$s in duration and actuating voltage pulse superimposed on it, whose duration varied in the range of $10-100\,\mu$s, which ensured gas breakdown in a wide pressure range and further discharge combustion at relatively low input energy. To create a constant magnetic field of up to 0.15 T, there were used various-thickness rare-earth magnets located under a thin top layer of the working surface. The magnetic field was directed perpendicular to the surface so that the resulting electromagnetic force ensured the discharge motion along the surface (Fig. 1, *a*).

The observed processes were visualized by using the tracer-particle method (particles image velocimetry, PIV [10]) which was implemented at the Dantec Dynamics complex: camera Hi-Sence mk2 with the resolution of 1344×1024 px, laser Litron NanoL with the pulse power of 135 MJ. The measurement area was dusted by using a soot generator. The laser knife plane was oriented perpendicular to the streamlined surface along the discharge motion direction. Reconstruction of the velocity field from tracer images was carried out using crosscorrelation adaptive algorithms with the continuous window displacement, single grid division, and deformation of the computational domain [11]. The observation area size was 17×23 mm. The size of the cells within which the velocity vectors were calculated was 16×16 px; hence, the final velocity field consisted of 127×145 vectors. To increase the accuracy of determining the velocity fields of tracer particles, the velocity fields were averaged over $50-100$ pairs of images. In reproducing electrical pulses by the generator and synchronizing the process with PIV recording accurately to at least 100 ns, we succeeded in obtaining flow patterns related to specific

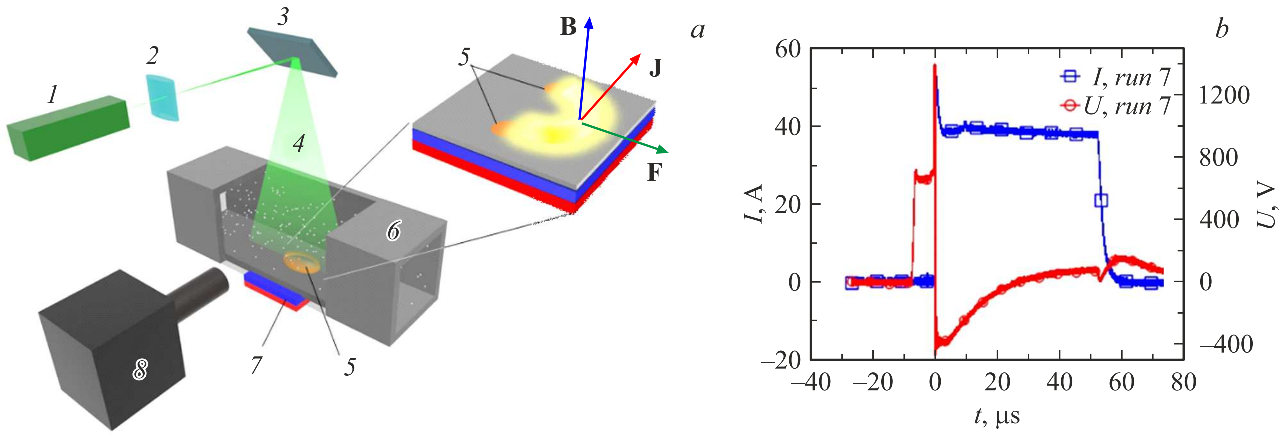

Figure 1. Schematic illustration for the experiment (*a*) and oscillograms of the discharge current and voltage (*b*). *1* — PIV-laser, *2* — lens system, *3* — mirror, *4* — laser knife, *5* — electrodes, *6* — working chamber, *7* — magnet, *8* — high-speed video camera.

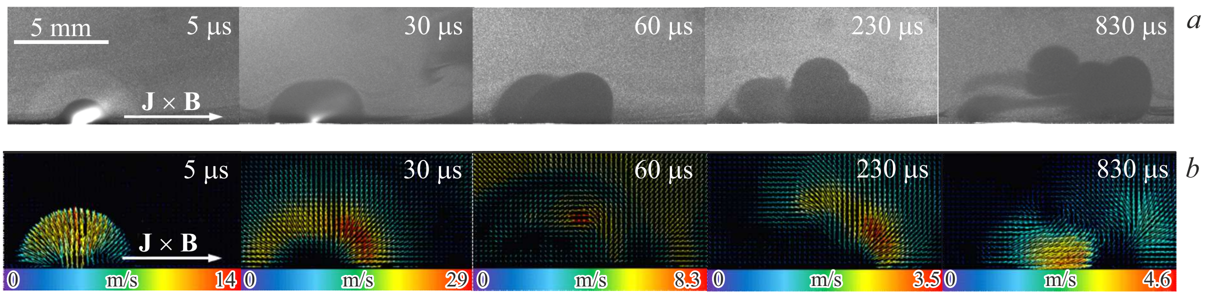

Figure 2. Air flow formation during the discharge motion in magnetic field of 0.1 T. *a* — instant photographs of the tracer microparticles distribution in the region of interaction, *b* — PIV visualization of the flow structure.

moments from the breakdown commencement. It has been established that the flow pattern occurring in the discharge motion central plane gets visible with high repeatability in each generated current pulse in at least 1 ms. Due to this, the PIV method enabled obtaiing averaged velocity fields with a high degree of detail.

In the course of work there was studied the process of the subsonic flow formation during the discharge motion in magnetic field. Analysis of the obtained images showed that the life cycle of a single discharge pulse can be divided into characteristic stages of the observed process evolution. Fig. 2, *a* presents the original photographs of microparticles in gas, which were illuminated by a laser knife for 15 ns. One can see that electrical breakdown accompanied by an abrupt increase in temperature and pressure results in formation in the near-electrode gas region of a low-density cavity that is a dark region with a very low density of tracer particles. Simultaneously with this, a cylindrical shock wave gets formed; at a distance of about the interelectrode gap, this wave transforms into a nearly-spherical wave. In 5 μs after the discharge commencement, the shock wave position and shape may be determined based on geometry of the gas region occupied by higher-density particles in 5 μs after breakdown. The light-color regionś outer boundary stands apart the shock wave at a certain distance matching the tracer particle relaxation rate. The figure also shows that the electric discharge plasma is pulled along the surface under electromagnetic force $\mathbf{J} \times \mathbf{B}$, where $\mathbf{J}$ is the arc current density, $\mathbf{B}$ is the magnetic field strength. After the discharge 50 μs in duration gets attenuated, there begins a stage characterized by continuing enlargement of the cavity region whose shape extends in the direction of the initially applied pulse in the cross-section under observation. As the cavity expands, it loses its speed, shape uniformity and density. One can see that particles rush from the surrounding gas into the low-pressure region in its tail. In 200 μs, there begins the cavity-collapse stage followed by violation of its integrity and uniformity. The fields of instantaneous velocities of the flow obtained by processing the initial data are presented in Fig. 2, *b*. The measurements allow qualitative determination of areas with high and low gas velocities and, in addition, dynamics of variations in the gas motion intensity with spreading of the low-pressure cavity. It is clear that, if the gas velocity gets significantly increased in the cavity head part during the electromagnetic force action, then it significantly increases at the stage of cavity collapse in its tail. Notice that unsteadiness of the dischargeś impact on the surrounding gas makes the tracer particles move with a nonuniform acceleration. Therefore, this

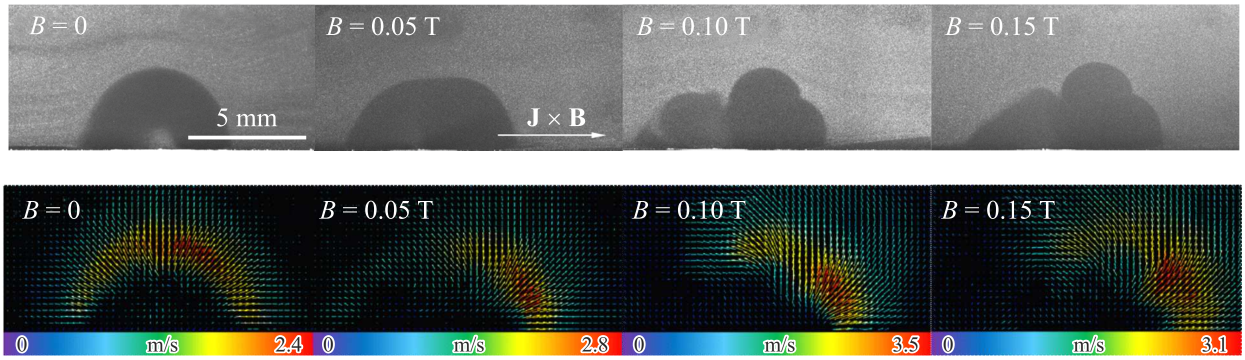

Figure 3. Variations in the structure of the discharge-induced flow in 230 μs after breakdown at different magnetic field magnitudes.

method is likely to give rise to a significant difference between the instantaneous velocity of particles and real gas velocity.

Evolution of the near-surface flow formed either under the electromagnetic force or in its absence was considered at different magnetic field magnitudes near the working surface ($B = 0-0.15$ T). Figure 3 demonstrates the flow patterns obtained in 230 μs after the discharge commencement. The figure shows that the speed of low-density cavity propagation in the direction of the electromagnetic force action increases with increasing magnetic field, which is confirmed by the cavity region „spread" along the surface. In addition, the uniform spherical shape of the cavity formed without magnetic field transforms into a complex vortex-flow structure consisting of two regions; these regions are especially clearly visible at $B = 0.1$ and 0.15 T. Thus, the magnetic field magnitude affects not only the maximum speed of the gas jet being formed, but also the flow decay rate; this is because of its early turbulization at higher local Reynolds numbers. This assumption is confirmed by the maximal values of instantaneous gas velocity measured by the PIV method. Notice once again that patterns of the vector fields of velocity allow only qualitative comparison of the observed unsteady phenomena. Determination of the true gas velocity requires additional research into the dynamics of accelerated particles under a nonstationary impact. However, we can confidently conclude based on the data obtained that the area of the discharge influence on the stationary gas extends with increasing magnetic field predominantly along the surface.

Thus, this study has demonstrated for the first time the evolution of a near-wall flow formed as a result of motion of the submillimeter electric discharge plasma under the action of electromagnetic force at different magnetic fields and at the atmospheric pressure. Results of the study allow suggesting that the considered type of actuator may be used to efficiently affect the structure of the near-wall flow formed in the case of either subsonic or supersonic over-plane flow.

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Conflict of interests

The authors declare that they have no conflict of interests.

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